

Ka-band High-Rate Downlink System for the NISAR Mission

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Abstract

This paper provides a description and analyses of the high-rate Ka-band telecom system for the upcoming NISAR (NASA-ISRO Synthetic Aperture Radar) mission. NISAR is a collaborative Earth-Science mission between National Aeronautics and Space Administration (NASA) and Indian Space Research Organization (ISRO), which features an L-band SAR instrument and an S-band SAR instrument. The simultaneous dual-frequency radar system at peak rates will produce data at gigabit-per-second speeds, which drives the data-volume requirements. The key driving requirement for the payload communication subsystem is to provide a minimum of 26 Terabits per day of radar science data to the ground. The high-rate transmitter on the flight system is a software-defined radio developed at the Jet Propulsion Laboratory (JPL), based on the Universal Space Transponder platform, providing an offset quadrature phase shift key modulated waveform with Low-Density Parity-Check encoding of the data transfer frames. Two transmitters used in a dual-polarization configuration with each transmitter providing two giga-symbols per second (Gsps) of coded data provides an aggregate rate of four Gsps. In this system, only one watt of signal power is necessary on each polarization to overcome propagation losses and achieve a successful RF link. Several Near Earth Network (NEN) ground station sites (Alaska in the United States, Svalbard in Norway, and Punta Arenas in Chile) are baselined for the space-to-Earth communications link. Each ground station will also feature multiple upgrades to support NISAR's transmission starting with new Ka-band antennas, wideband downconverters and high-rate receivers. In addition, a baseband data processor called Data Acquisition Processor and Handling Network Environment (DAPHNE), newly developed by the NEN, provides data storage and connectivity to backhaul networks. With NISAR's large quantities of data (over 3.5 Petabytes over the mission), the processing of science data will be primarily performed on a cloud system to reduce the overall cost to the mission. The system described herein will be the first operational use of Gsps-class downlink rates on an Earth-Science mission.

Keywords: Ka-band Propagation; Software defined radio; Satellite communication; Big data;

1. Introduction

An inaugural collaboration mission between the National Aeronautics and Space Administration (NASA) and the Indian Space Research Organization (ISRO) is underway for the deployment of an all-weather radar mission to make integrated measurements of the causes and consequences of land-surface changes. The NASA-ISRO Synthetic Aperture Radar (NISAR) mission aims to observe and quantify the overall Earth change of highly spatial and temporally complex processes such as solid-earth deformation, ice-sheet collapse, biomass vegetation levels, and natural hazards such as earthquakes, tsunamis, volcanoes, and landslides. The world's first dual-frequency (L- and S-band) SweepSAR observatory [1] will enable meeting NISAR's far-reaching science objectives.

NISAR concept of operation places it in near-polar, sun-synchronous orbit with a 12-day repeat cycle at an index altitude of 747 km. A shared 12-meter parabolic reflector mounted on a 9-meter boom (Fig. 1) provides a

wide radar swath over 240 km in width at fine resolution. To meet this wide-swath requirement, an array feed of 12 L-band Transmit Receive (T/R) modules per polarization and an array feed of 24 S-band T/R modules per polarization will be used [2]. At peak data collection, both radar instruments will be generating data at gigabit-per-second speeds (2.4 Gbps at L-band, and 3.8 Gbps at S-band) [3] which are stored in the high-speed, high-capacity (12 Terabit) Solid State Recorder (SSR) until downlinking to the ground. The overall data collection sums to between 23-30 Terabits per day, averaging slightly less than 25.5 Terabits per day.

The flight-system configuration carries two independent Ka-band transmit systems that allows the downlinking of science and engineering data to each respective space agency's ground facility. Both Ka-band systems are dual-polarization systems with the downlink signal transmitted using left-hand and right-hand circular polarizations in the Earth Exploration

Satellite Service (EESS) band from 25.5 to 27.0 GHz. The ISRO Ka-band downlink system carries three transmitters on each polarization (six total transmitters) to support an aggregate information rate of 2.25 Gbps, or 2.88 Gbps coded rate using (255, 239) Reed-Solomon coding and 8 Phase Shift Key (PSK) modulation to ISRO's Ka-band ground station at Shadnagar, India. The same science and engineering data can be downlinked with the NASA transmitters at an aggregate information rate of 3.45 Gbps, or 4.0 Gbps coded rate using Low Density Parity Check (LDPC) coding and Offset Quadrature PSK (OQPSK) modulation to NASA's Near Earth Network (NEN) ground stations. The focus of this paper is the telecom system developed for NASA at the Jet Propulsion Laboratory (JPL), referred to as the Payload Communication Subsystem (PCS), and the space link to the NEN ground stations to support 26 Tbits/day of science-data return.



Fig. 1. Artist's concept of NISAR spacecraft in deployed flight configuration

2. Payload Communications Subsystem

Fig. 2 is the simplified block diagram of the two NISAR transmitter systems and the shared telecom elements. The 12 Terabit high-capacity SSR stores the instrument data from both L- and S-band SAR systems for downlinking by either transmitter systems. The two systems share a 70-cm diameter high-gain antenna (HGA), a dual gimbal assembly (DGA) for pointing and steering, and waveguide transfer switches (WTS) for switching between the two systems.

For the NASA Ka-band downlink system, a high-rate transmitter version of the Universal Space Transponder software-defined radio [4] developed at

JPL provides OQPSK modulation at 2.0 Gbps with LDPC encoding [5]. Two such Ka-band Modulator (KaM) transmitter units used simultaneously provides the aggregate 4.0 Gbps rate.

The SSR formats the instrument data into Consultative Committee for Space Data Systems (CCSDS) Advanced Orbiting Systems (AOS) Transfer Frames and transfers them to each KaM transmitter over a high-speed interface at 2.4 Gbps line rate. The KaM uses the (8160, 7136) CCSDS LDPC forward error correction coding (commonly referred to as LDPC-7/8) which provides more than 2.5 dB of coding gain improvement over conventional Reed-Solomon codes at a bit error rate (BER) of $1e-8$. Unlike Turbo codes with an error-floor limitation typically around $1e-7$ BER, the CCSDS LDPC code exhibits no error floors for at least two decades lower [6]. However, the LDPC encoding by itself does not guarantee sufficient bit transitions for the ground receiver to maintain symbol synchronization, and thus a length-255 pseudo-randomizer is used in addition. The KaM OQPSK modulates the in-phase and quadrature (I/Q) components of the symbol stream on a 26.25 GHz carrier signal. The offset I/Q transitions reduces power fluctuations at the zero-crossing by avoiding simultaneous I/Q transitions, thereby making it resilient to spectral regrowth from the downstream saturated amplifier [7].

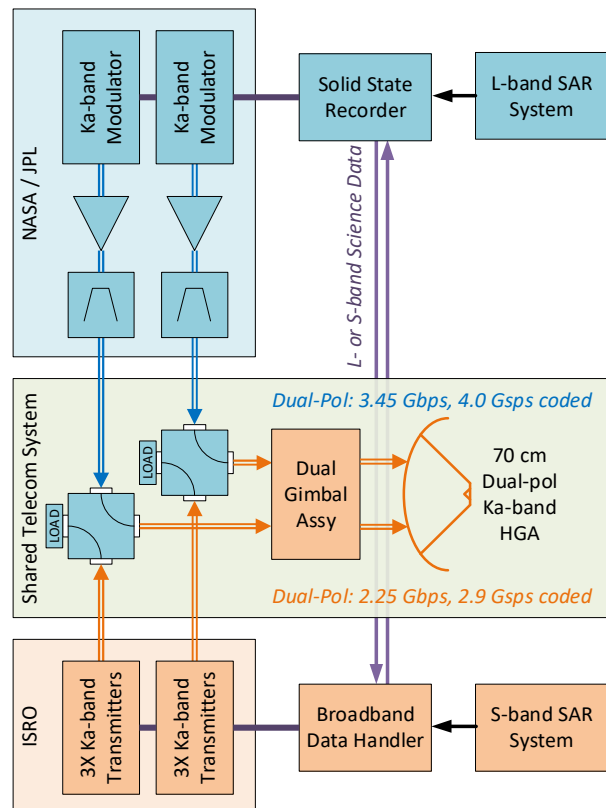


Fig. 2. NISAR Ka-band telecom system block diagram



Fig. 3. NISAR Ka-band Modulator transmitter

Both baseband filtering and RF passband filtering (before and after the SSPA respectively) ensures compliance to the spectral-emissions allocation of 1.5 GHz from the National Telecommunications and Information Administration (NTIA). Fig. 4 depicts the simulated OQPSK waveform power spectral density (PSD) as it is baseband filtered. Further simulations show that about 10 dB of spectral regrowth occurs due to the compressed amplifiers in the transmit chain (Fig. 5), and so the use of RF passband filtering post amplifier is essential. The estimated total band-limiting loss is approximately 1.0 dB including other non-linear phase elements in the transmit chain like the DGA.

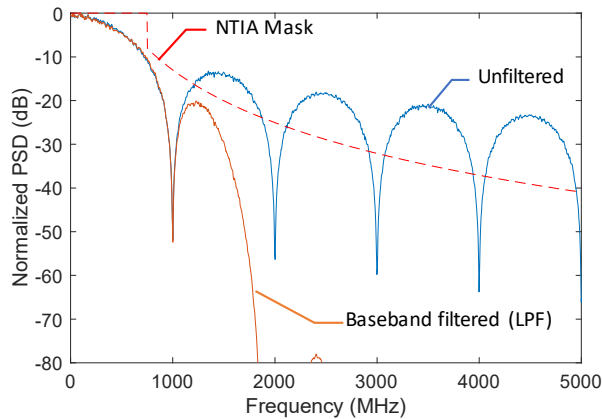


Fig. 4. Baseband filtered power spectral density

The ISRO-provided 70-cm HGA has 41 dBi peak gain and a 0.5 dB beam width of $\pm 0.23^\circ$. The high humidity environment in India incurs high atmospheric attenuation and the large aperture size is necessary to close ISRO's Ka-band transmissions. In contrast, transmissions to drier environments (such as those proposed for JPL transmissions) benefit higher link margin and can afford reduced signal power. The link budget presented later shows ample link margin (greater than 6 dB) with only one watt of RF signal power per

polarization. The antenna's narrow-beam design, combined with limiting transmissions to only during a ground-station overflight minimizes potential Ka-band interference and promotes efficient use of shared Ka-band ground-station resources.

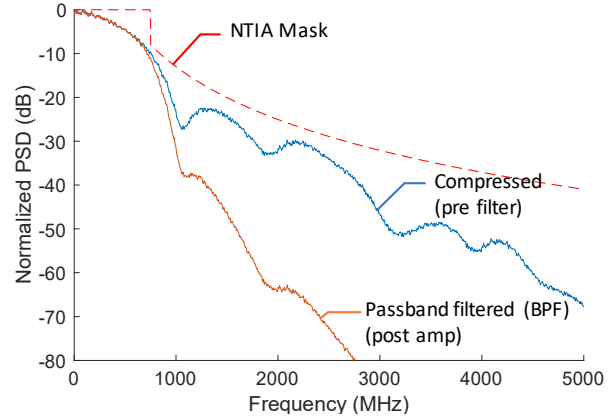


Fig. 5. Spectral regrowth and RF passband filtering

3. Proposed Ground Stations

In addition to significant capability increase on the flight system side, the NEN ground stations managed by NASA's Goddard Space Flight Center (GSFC) are also in need of upgrades to support the reception and decoding of Ka-band signals at these high rates and large data volumes [9]. Proposed ground station sites are at high latitude (such as Svalbard, Norway) to provide increased access opportunity for NISAR's near-polar orbit. The high-latitude regions also typically exhibit drier weather conditions that provide lower moisture-induced depolarization effects, critical in dual-polarization transmission links. Fig. 6 maps the proposed facility locations for NISAR's transmission.



Fig. 6. Proposed ground station sites

Orbit and coverage analysis to the proposed ground station sites show average track durations of 8 to 9 minutes long with valid passes constrained to a minimum 10° elevation angle and minimum track duration of 180 seconds. The analysis shows that using all track opportunities fully could allow up to 43.9 Tbits/day of downlinked data (see Table 1).

Table 1. Coverage analysis to NEN ground stations

Facility	Avg. Passes	Avg. Dur.	Capability
ASF	9.3/day	8.0 min	15.1 Tb/day
SGS	11.5/day	8.8 min	20.3 Tb/day
PAS	5.1/day	8.2 min	8.5 Tb/day

The proposed ground stations for upgrade will each have a prime and backup 11.3-meter tri-band S/X/Ka subreflectors providing 67.7 dBi of gain with a clear-sky gain-to-noise-temperature (G/T) value of 41.4 dB/K. New high data-rate receivers (HDR) at each antenna asset performs the acquisition, tracking, demodulation, and decoding of the dual-polarization transmit stream from NISAR.

The unprecedented data volume produced by NISAR (a minimum of 26 Tb/day equates to over 3.5 Petabytes of data over the course of the mission) requires new methods for data processing and access. The delivery of large quantities of data over traditional networks is costly and uneconomical, so a cloud system will primarily process the science data to reduce the overall mission cost. The Data Acquisition Processing and Handling Network Environment (DAPHNE) developed at the NEN provide access for NISAR's operations and science teams.

DAPHNE is comprised of two systems called DAPHNE Lite and DAPHNE Cloud. The DAPHNE Lite system is local at each antenna asset and is responsible for capturing the data from the HDR, handles virtual channel prioritization, and delivers data to the cloud network. The DAPHNE Cloud system provides the longer data storage for data processing in the cloud, and is responsible for sorting and delivery of processed data to the operators and science teams.

4. Ka-band Atmospheric Propagation Effects

Accurate statistics on atmospheric effects at NASA's Deep Space Network (DSN) stations rely on multiyear sky brightness temperature measurements taken over the last 50 years using water vapor radiometers (WVR) equipped at each site. The introduction of Ka-band links is only in recent years and weather statistics are still preliminary at the proposed sites. The International Telecommunication Union (ITU) provides global data and models to estimate the propagation effects, but large uncertainties, and thus large total atmospheric losses, remain. Comparisons between the ITU model and the WVR statistics collected at the DSN sites show the ITU models are in reasonable agreement but some discrepancies up to 1.5 dB at 99% weather remain, likely due to higher uncertainties with the liquid content models (rain and clouds) at higher percentiles [8]. Table 2 summarizes the atmospheric attenuation values calculated from the ITU model, used in the link margin calculations. With NISAR's deployment and continued use at Ka-band in

the coming years, measured statistical values for atmospheric attenuation will become available for future mission planning.

Table 2. Atmospheric attenuation estimates in dB at 10° elevation angle and 99% weather

Attenuation Effect	ASF	SGS	PAS
Gaseous absorption	1.17	0.94	1.59
Rain	3.07	1.19	1.99
Scintillation/Multipath	0.53	0.51	0.68
Cloud	2.57	2.54	3.37
Total Effects	6.83	4.70	6.99

4. Link Analyses

Table 3 shows the simplified link budget to all proposed NEN ground stations at 10° elevation angle and 99% weather for 1e-8 BER using LDPC-7/8 coding. Link margins to all proposed facilities have ample margin greater than 6 dB.

Table 3. Simplified link budget to NEN ground stations

Link Parameter	Units	ASF	SGS	PAS
Tx Power	dBW	0.0	0.0	0.0
Circuit Loss	dB	-2.5	-2.5	-2.5
Tx Ant Gain	dBi	41.0	41.0	41.0
Pointing Loss	dB	-0.5	-0.5	-0.5
EIRP	dBW	38.0	38.0	38.0
Pol Loss	dB	-0.1	-0.1	-0.1
Path Loss	dB	-187.9	-187.9	-187.9
Atmos Loss	dB	-6.8	-4.7	-7.0
G/T + Loss	dB/K	39.6	40.3	40.1
XPOL degrad	dB	-3.6	-5.0	-3.6
CNR Density	dB-Hz	107.8	109.2	108.1
Info Rate	dB-bps	92.4	92.4	92.4
Rx Eb/No	dB	15.3	16.8	15.7
Radio Loss	dB	-4.5	-4.5	-4.5
Req Eb/No	dB	4.1	4.1	4.1
Link Margin	dB	6.7	8.2	7.1

The Radio Loss of 4.5 dB shown in Table 3 includes performance degradation effects incurred at both the transmit and receive ends. This includes transmit filtering power losses (band-limiting losses), distortion effects from compressed amplifiers, receiver symbol timing errors, carrier tracking and phase reconstruction errors, and inter-symbol interference (ISI). This so-called radio implementation loss was determined by performing BER measurements against commercially available high-rate receivers and the engineering model of the KaM transmitter.

Another important effect to consider for dual-polarization systems is the cross-polarization (XPOL) degradation from moisture-induced depolarization effects, typically from rain. As radiated waves pass

through asymmetrical rain drops, the incident wave becomes depolarized and cross-polarization interference occurs. In a worst-case scenario, this effect can phase combine with the transmit and receive antenna's non-ideal axial ratios and further introduce polarization loss. Stutzman's model [10] shows the cross-polarization discrimination (XPD) for a 26.25 GHz circular-polarized signal at 10° elevation angle to be > 30 dB. The XPOL degradation shown in Table 3 is primarily due to the poor polarization isolation from the DGA and HGA. A reduction in this degradation value is expected once test data from the flight model is measured.

6. Conclusions and Future Work

This paper discussed the JPL high-rate Ka-band telecom payload for the NISAR mission to downlink 26 Tbits/day of science and engineering data from the two on-board SAR systems. Propagation analyses and link performance analyses show ample margin to close the link to the proposed ground station assets. The system described will be the first operational use of gigabit-class downlink rates on an Earth-Science mission and provides a pathway for future missions with big-data requirements.

Additional research and development for future work includes employing higher-order modulation schemes such as 16-APSK and using a dual SERDES input to achieve data rates up to 7.0 Gbps from a dual-polarization transmit system. Also, variable Coding and Modulation or Adaptive Data Rate schemes could take advantage of the increasing signal-to-noise ratio as a spacecraft reaches higher elevations over the ground station to increase the science-data return.

The NISAR mission is currently in the flight hardware development cycle with three flight units in assembly. These flight models will undergo a complete proto-flight qualification program in early 2019 and integrated to the payload communications subsystem. NISAR is to launch no earlier than December 2021.

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